LBL-10314 c.2
Preprint

4/17

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

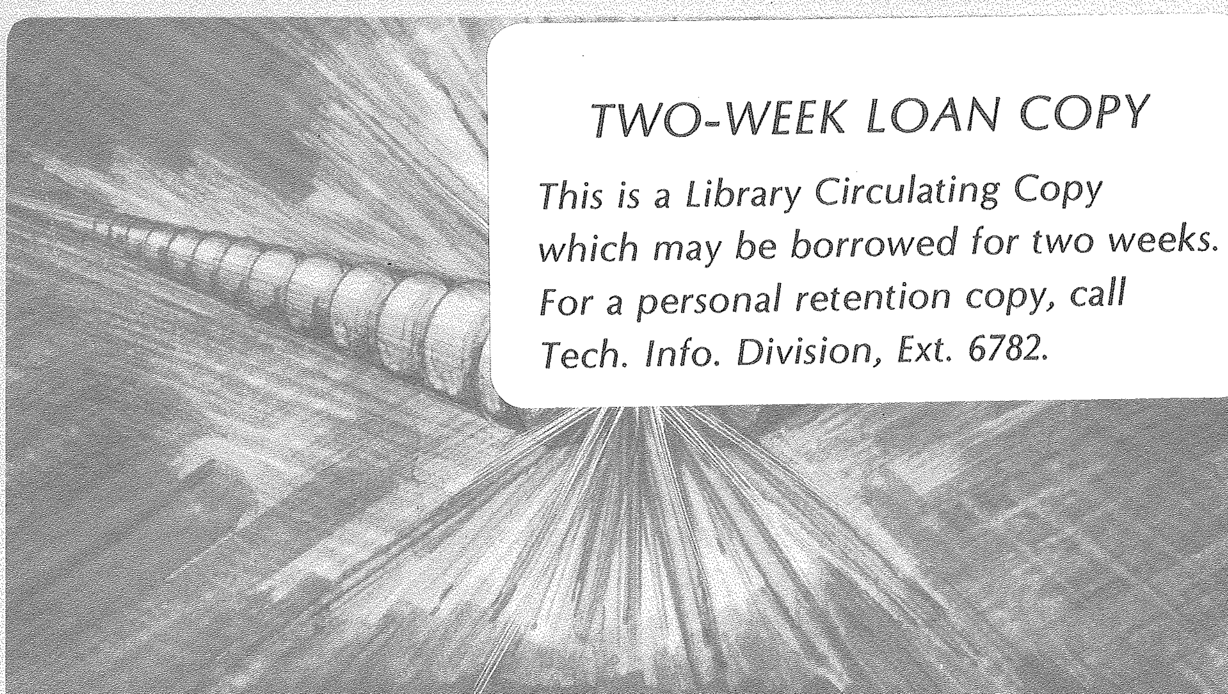
Accelerator & Fusion Research Division

Submitted to Physical Review Letters

EVOLUTION OF PROJECTILE DOUBLE K VACANCY FRACTIONS WITH TARGET THICKNESS IN ION-ATOM COLLISIONS

J. A. Tanis, S. M. Shafroth, J. E. Willis,
and J. R. Mowat

January 1980



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

Phys. Review Letters LBL-10314

Evolution of Projectile Double K Vacancy Fractions with Target Thickness in Ion-Atom Collisions*

J. A. Tanis

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720
and
Physics Department, East Carolina University, Greenville,
North Carolina 27834

S. M. Shafroth and J. E. Willis

Department of Physics and Astronomy, University of North Carolina,
Chapel Hill, North Carolina 27514
and
Triangle Universities Nuclear Laboratory, Durharm, North Carolina 27706

J. R. Mowat

Department of Physics, North Carolina State University,
Raleigh, North Carolina 27607

ABSTRACT

The dependence of projectile double K-vacancy (hypersatellite) x-ray yields on target thickness for ions moving in thin solid targets is examined. For 2.3 MeV/amu Cl ions incident on C foils, the double-to-single K vacancy x-ray yield increases by a factor of 3.5 over the range of thicknesses investigated, reaching values as high as 30%. A quantitative explanation of the observed results is obtained using the three-component model of Gardner et al.

*Work supported in part by the U. S. Department of Energy, Division of Chemical Sciences, and Office of Fusion Energy under contract W-7405-ENG-48.

The production of ions with two K vacancies is of fundamental interest in ion-atom collisions[1-3]. Usually, double K-vacancy production is inferred from the ratio $R = \sigma_x^h/\sigma_x$ of hypersatellite- to-single K vacancy x-ray yields, assuming the fluorescence yields for single and double K vacancies are the same.[1] This ratio has also been used to determine double K vacancy sharing ratios between target and projectile in near symmetric collisions.[3] Furthermore, the experimental determination of branching ratios for two-electron-one-photon transitions usually requires a separate measurement of the double-to-single K vacancy x-ray yield R[4,5]. In the above cited works, it was tacitly assumed that R does not depend upon the target thickness.

In this letter we show that the evolution of double K vacancies relative to single K vacancies for an ion passing through a solid target results in values for R which are strongly dependent on foil thickness. For Cl ions incident on C foils, the measured values of R change by a factor of 3.5 over the range of thicknesses examined, reaching values as high as 0.30. By modelling the production and filling of K vacancies following the methods of Gray and coworkers[6,7], based on the original formulation by Allison[8], we obtain a quantitative description of the observed results. Similar analyses have previously been used to interpret both target[6,7] and projectile[9-11] single K-vacancy x-ray production in heavy ion-atom collisions.

Single and double K vacancy x-ray intensities have been measured for 2.3 MeV/amu (80 MeV) Cl^{10+} ions incident on thin (10-150 $\mu g/cm^2$) C foils. Spectra were recorded by standard techniques and have been described elsewhere[12]. X rays were detected in air at 90^o to the beam with a Kevex Si(Li) detector. The detector viewed the target through a 25.4 μm Mylar window. In order to keep pileup and dead time effects to a minimum, count rates were held to $\lesssim 400$ counts/sec by placing a 12.7-μm aluminum absorber in front of the detector. A silicon surface barrier detector was used for normalization of the incident beam intensity. A cylindrical scattering chamber had provision for rotating the particle detector. Absolute detector efficiency was calculated using tabulated photon absorption cross sections[13] for the various absorbers between target and detector. In addition, the detector efficiency was determined experimentally using measured x-ray cross sections for 3 MeV protons[14]. The two efficiency determinations agreed to within 15%.

Typical x-ray spectra for two foil thicknesses are shown in Fig. 1. It is seen that a shoulder appears on the high energy side of $K\alpha$, while, in the case of $K\beta$, the presence of two peaks is evident. The higher energy peak in each case is identified as being due to x-ray transitions in the presence of two K vacancies, i.e. hypersatellite transitions denoted by K_α^h and K_β^h respectively. The change in relative x-ray yields with foil thickness is readily apparent.

The intensities of each of the four peaks were determined from a least squares analysis of the spectrum, assuming Gaussian line shapes. These intensities were corrected for absolute detection efficiency. Resulting x-ray production yields $\bar{\sigma}_x$ and $\bar{\sigma}_x^h$ for single and double K vacancies, respectively, are shown in Fig. 2 plotted as a function of target thickness. ($\bar{\sigma}_x$ is the sum of the $K\alpha$ and $K\beta$ transition intensities while $\bar{\sigma}_x^h$ is the sum of the K_α^h and K_β^h intensities). It is seen that the single K-vacancy x-ray yield $\bar{\sigma}_x$ decreases with target thickness in agreement with previous results for Cl + Cu[11,12] while the hypersatellite yield $\bar{\sigma}_x^h$ increases with target thickness. The curves through the $\bar{\sigma}_x$ and $\bar{\sigma}_x^h$ data will be discussed below.

In order to interpret these results it was assumed that the single K-vacancy data $\bar{\sigma}_x$ could be described within the framework of the two-component model[6] with the hypersatellite data $\bar{\sigma}_x^h$ treated as a perturbation of this model. Since the hypersatellite intensity reaches 30% of the single K-vacancy intensity only for the thickest targets, this is probably a reasonable assumption.

A least squares analysis of $\bar{\sigma}_x$ was performed using the two-component model following the procedure of Refs. 11 and 12. The result of the least squares fit is shown by the dashed curve in Fig. 2. The fitting parameters are listed in Table I. σ_{01} and σ_{10} are the formation and loss cross sections, respectively, for a single vacancy. ω_K and λ_x are additional parameters which are needed to characterize the x-ray production: ω_K is the mean fluorescence yield for the highly stripped projectile and λ_x is the radiative decay probability per unit path length in the target. (In refs. 11 and 12 σ_{01} is denoted by σ_v the vacancy production cross section, and σ_{10} is denoted by the sum $\sigma_c + \sigma_\tau$ where σ_c is the cross section for capture to the K-shell and σ_τ is the cross section for radiative or Auger decay.)

In order to interpret the hypersatellite data we must formulate an expression for the measured $\bar{\sigma}_x^h$ as a function of target thickness. Contributions to the hypersatellite intensity from decays inside the foil and outside the foil must be considered separately. Inside the foil, the hypersatellite intensity dN_h^i arising from an elemental thickness dx of the foil is given by

$$dN_h^i = I_o Y_2(x) \lambda_x^h dx \; \varepsilon \qquad (1)$$

where I_o is the total number of incident ions, $Y_2(x)$ is the fraction of ions at x with two K vacancies, λ_x^h is the hypersatellite decay probability per unit path length, and ε is the detection efficiency. Outside the foil the hypersatellite intensity N_h^o is

$$N_h^o = I_o Y_2(T)\omega_K^h \varepsilon \tag{2}$$

where Y_2 is evaluated at T, the foil thickness, and ω_K^h is the hypersatellite fluorescence yield.

For the fraction of ions Y_2 with two K vacancies we use the expression from the three-component formulation of Allison[8]. Since there are three beam components, there are six charge changing cross sections $\sigma_{01}, \sigma_{10}, \sigma_{12}, \sigma_{21}, \sigma_{02}, \sigma_{20}$ which describe formation and loss of 0,1, or 2 K vacancies. (We use the notation of ref. 8.) With this expression for Y_2, eq.(1) is integrated over foil thickness and the result is used in conjunction with eq. (2) giving an expression for the hypersatellite production cross section $\bar{\sigma}_x^h$ for a foil of thickness T

$$\begin{aligned} \bar{\sigma}_x^h(T) = \lambda_x^h\{Y_{2\infty} - \frac{P}{f_1 T}(1-e^{f_1 T}) + \frac{N}{f_2 T}(1-e^{-f_2 T})\} \\ + \frac{\omega_K^h}{T}\{Y_{2\infty} + Pe^{f_1 T} + Ne^{-f_2 T}\} \end{aligned} \tag{3}$$

where $Y_{2\infty}$ is the equilibrium fraction of ions with two K vacancies and P, N, f_1 and f_2 are functions of the six K-vacancy formation and loss cross sections σ_{ij} where i, j = 0, 1, 2 and $i \neq j$.[8]

We now wish to see if the hypersatellite data shown in Fig. 2 can be described with eq. (3). A least squares fit to the data will not give meaningful results since the eight free parameters--namely, λ_x^h, ω_K^h and the six σ_{ij}'s--cannot be determined independently. A more stringent test of the validity of eq. (3) is acehived if, by choosing reasonable values for the eight parameters, the foil thickness dependence of σ_x^h can be predicted.

The values chosen for the parameters are shown in the second row of Table I. σ_{01} and σ_{10} were taken to be equal to the values obtained from the two-component analysis of the single K-vacancy data. σ_{02} can be estimated by extrapolating $\bar{\sigma}_x^h$ to zero target thickness, where $\sigma_{02} = \bar{\sigma}_x^h(0)/\omega_K^h$ and ω_K^h was taken to be equal to the single K-vacancy value ω_K. The double capture cross section σ_{20} should be small and was arbitrarily chosen to be slightly smaller than σ_{02}. In any case, because of its relative smallness, σ_{20} has little effect on either the magnitude or thickness dependence of $\bar{\sigma}_x^h$ calculated from eq. (3). σ_{12} is expected to be nearly equal to σ_{01} except that σ_{12} may be slightly smaller due to an increase in the K-shell binding energy when there is only a single K-electron. σ_{21} should be about twice as large as σ_{10} since these vacancy loss cross sections are largely due to capture and an ion with two K vacancies should be about twice as likely to capture an electron. (In addition to capture, radiative and Auger transitions contribute to σ_{21} and σ_{10}.) Finally, λ_x^h was taken to be equal to the single vacancy value λ_x.

The values listed in Table I were substituted into eq. (3) giving the predicted values for $\bar{\sigma}_x^h$. The results are shown by the smooth curve in the lower part of Fig. 2. The agreement with the experimentatal data is seen to be excellent. The model predicts that $\bar{\sigma}_x^h$ decreases for foil thickness $\gtrsim 70\ \mu g/cm^2$ and the data tend to confirm this trend. The upper part of Fig. 2 shows the ratio of double to single K-vacancy x-ray intensities. Again the agreement between the measured and calculated values is excellent. The calculated values for $\bar{\sigma}_x$ were taken from the dashed curve in Fig. 2.

The effect of the above results on the determination of single-to-double K-vacancy production in heavy ion-atom collisions is evident. Usually this vacancy ratio is inferred, without regard to target thickness, from the x-ray production yields assuming that the fluorescence yields for single and double K vacancies are nearly the same[1]. From Fig. 2 it is seen that this ratio can change by a factor of 6 in going from zero to equilibrium target thickness, thereby casting uncertainty on results obtained by this method. Furthermore, double K-vacancy sharing ratios have been deduced from measurements of single-to-double K-vacancy x-ray intensity ratios for target and projectile in near symmetric collisions[3]. The sharing ratios so obtained may have to be re-examined in view of the results presented here.

Another area of investigation which is directly affected by the results presented here is the determination of the branching ratio $K_{\alpha\alpha}^h/K_\alpha^h$ for two-electron-one-photon transitions,[4,5] where $K_{\alpha\alpha}^h$ is the correlated two-electron-one-photon transition intensity. This branching ratio is usually detemined from separate measurements of the ratios $K_{\alpha\alpha}^h/K_\alpha$ and K_α^h/K_α. Since the measurement of $K_{\alpha\alpha}^h/K_\alpha$ and K_α^h/K_α require different experimental techniques, care must be taken to use foils of the same thickness. If this is not done, then the branching ratio so obtained will be in error.

In summary, we have measured the variation in projectile hypersatellite x-ray yield as a function of target thickness and we have shown that this variation is quite different from that of single K-vacancy x-ray yields. Using the three-component model[7,8] to describe the evolution of double K-vacancy fractions with target thickness, we have shown that not only the functional dependence but the absolute magnitude of the observed x-ray yields could be predicted. Excellent agreement is obtained between our data and the model predictions given by eq. (3) with no adjustment of parameters.

The results presented here clearly establish the need to include the effects of target thickness in comparisons of single and double K-vacancy production in ion-atom collisions.

REFERENCES

1. C. W. Woods, F. Hopkins, R. L. Kauffman, D. O. Elliott, K. A. Jamison, and P. Richard, Phys. Rev. Lett. 31, 1 (1973).
2. J. S. Greenberg, P. Vincent, and W. Lichten, Phys. Rev. A16, 964 (1977).
3. P. Richard, J. M. Hall, C. Schmiedekamp, and K. A. Jamison, Phys. Rev. A18, 940 (1978).
4. Ch. Stoller, W. Wölfli, G. Bonani, M. Stöckli, and M. Suter, Phys. Rev. A15, 990 (1977).
5. R. Schuch, G. Gaukler, and H. Schmidt-Böcking, Z. Phys. A290, 19 (1979).
6. T. J. Gray, P. Richard, K. A. Jamison, and J. M. Hall, Phys. Rev. A14, 1333 (1976).
7. R. K. Gardner, T. J. Gray, P. Richard, C. Schmiedekamp, K. A. Jamison, and J. M. Hall, Phys. Rev. A15, 2202 (1977).
8. S. K. Allison, Rev. Mod. Phys. 30, 1137 (1958).
9. H.-D. Betz, F. Bell, H. Panke, G. Kalkoffen, M. Welz, and D. Evers, Phys. Rev. Lett. 33, 807 (1974).
10. J. A. Tanis and S. M. Shafroth, Phys. Rev. Lett. 40, 1174 (1978).
11. J. A. Tanis and S. M. Shafroth, Jap. Jour. App. Phys. 17, Suppl. 17-2, 399 (1978).
12. J. A. Tanis, W. W. Jacobs, S. M. Shafroth (submitted to Phys. Rev. A).
13. E. Storm and H. I. Israel, Nucl. Data Tables A7, 565 (1970).
14. C. H. Rutledge and R. L. Watson, ADNDT 12, 195 (1973).

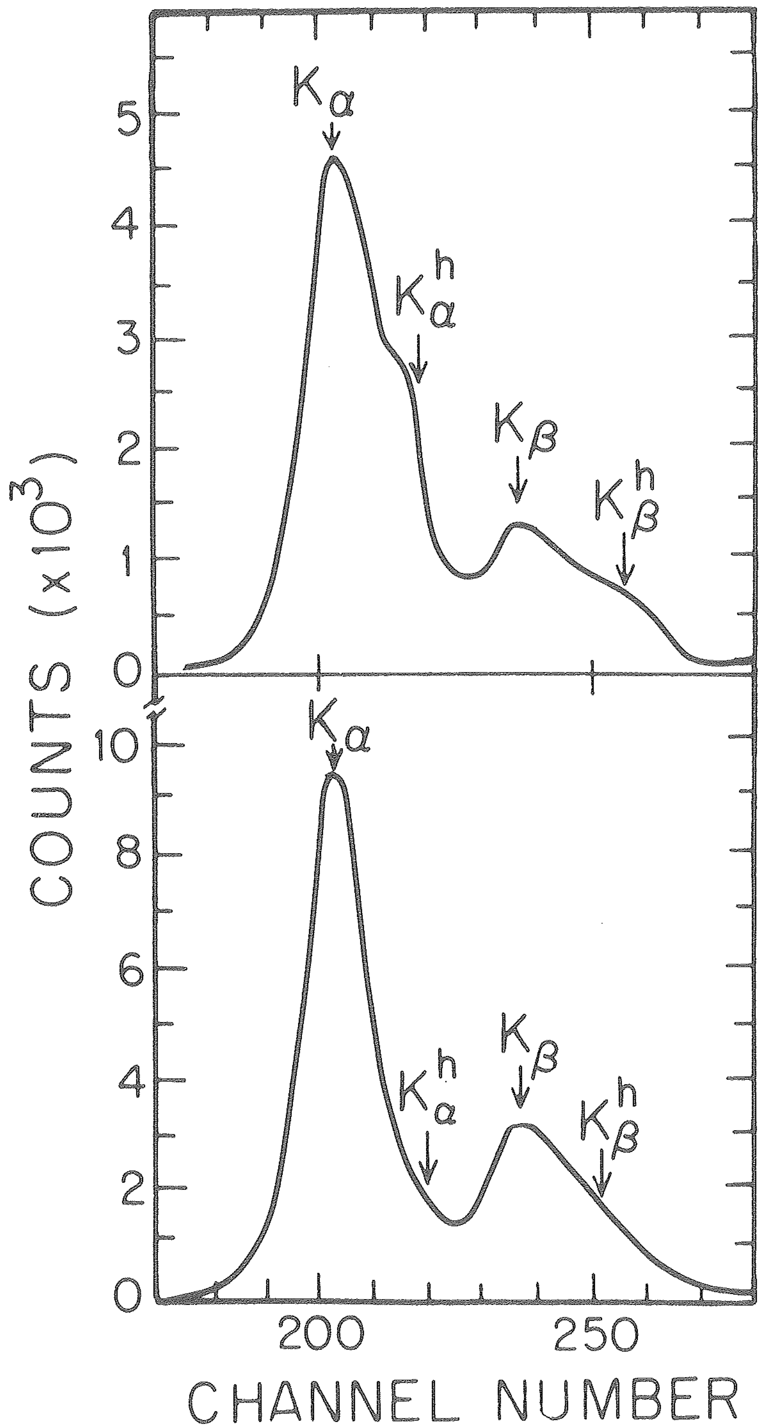
Table I. Values of formation and loss cross sections for K vacancies and values of radiative parameters required for the description of x-ray production, using the two- and three-component models (refs. 6-8).

Parameter / Model	σ_{01} (kb)	σ_{10} (kb)	σ_{12} (kb)	σ_{21} (kb)	σ_{02} (kb)	σ_{20} (kb)	ω_K	λ_x (kb)	ω_K^h	λ_x^h (kb)
Two-comp.	250	370	--	--	--	--	0.64	90	--	--
Three-comp.	250	370	200	600	12	10	0.64	90	0.64	90

FIGURE CAPTIONS

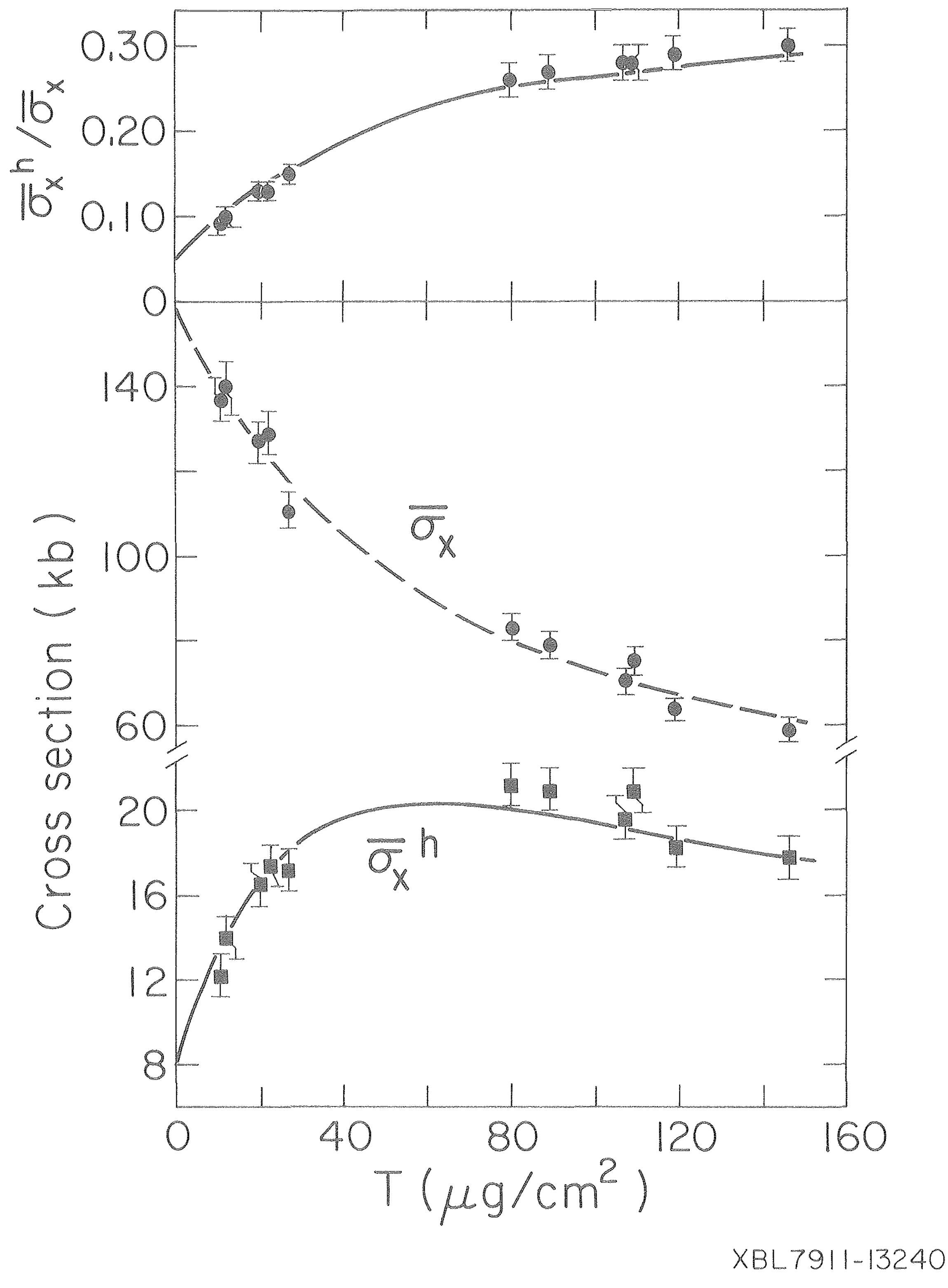
Fig. 1 Typical Cl K x-ray spectra for 80 MeV Cl^{10+} + C collisions for two foil thicknesses. X-ray peaks corresponding to single (K_α and K_β) and double (K_α^h and K_β^h) K vacancies are seen.

Fig. 2 Lower part: Measured single ($\bar{\sigma}_x$) and double ($\bar{\sigma}_x^h$) K-vacancy x-ray yields as a function of target thickness. The dashed curve through $\bar{\sigma}_x$ is a least squares fit based on the two-component model (ref. 6). The solid curve for $\bar{\sigma}_x^h$ was calculated from the three component model (refs. 7 and 8). Upper part: Measured ratio of double-to-single K vacancy x-ray intensities compared with calculated results.



XBL 803-8743

Fig. 1



$\overline{\sigma}_x^h/\overline{\sigma}_x$
0.30
0.20
0.10
0
140
100
60
20
16
12
8
$\overline{\sigma}_x$
$\overline{\sigma}_x^h$
Cross section (kb)
0
40
80
120
160
T (μg/cm^2)
XBL7911-13240

Fig. 2